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RESEARCH MEMORANDUM

PERMEABILITY VARIATION OF A TAPER-ROLLED WIRE CLOTH

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

The effect on the cloth permeability of rolling a tapering thickness on a 20×200-mesh stainless-steel wire cloth (0.0307 in. thick) was investigated experimentally. The application of the cloth considered herein was for the shell of a transpiration-cooled turbine blade operating at gas and shell temperatures of 2500° and 1000° F, respectively. From available design procedures, cloth thicknesses ranging from 0.0151 to 0.0225 inch were calculated for this application. These experiments were conducted for ranges of airflow rates of from about 0.0003 to 0.07 pound per second per square inch of cloth. The difference in the square of the pressure of the air before and after the cloth ranges from about 0.48 to 3533 ($lb^2/in.^4$).

Only slight effects were observed in the permeability variation within a sheet of the material when rolled with the taper parallel to the 200 wires. An appreciable effect on permeability and its variation within a sheet (400 percent variation in pressure-drop parameter) was observed, however, when the wire cloth was rolled with a taper in the direction perpendicular to the 200 wires. The pressure-drop data for the taper-rolled (perpendicular to the 200 wires) samples fell from 68 to 216 percent above the data for the flat-rolled samples of comparable thickness. This represents a change in required thickness of about 8 percent to bring the data into good agreement.

INTRODUCTION

An effective method of reducing temperatures of surfaces exposed to hot gas streams is transpiration cooling. The surfaces to be cooled are formed from a porous material. The coolant is forced through the surface, forming an insulating layer of fluid between the wall and the hot gas stream. Application of this cooling principle has been considered in cooling parts of gas turbines such as nozzles and rotor blades, combustion chambers, and afterburners. This principle is also applicable to the cooling of critical surfaces of bodies flying at high speeds.

Porous materials such as sintered metals or closely woven wire cloth may be suitable for the aforementioned applications. Research is being conducted on both materials to improve their physical and cooling characteristics. Only the wire cloth is considered herein.

In general, wire cloths of standard weaves are too permeable and must be processed in some manner to decrease permeability. Some experimental investigations have shown how rolling or combined brazing and rolling of wire cloth decrease the permeability (refs. 1 and 2). These references show that reducing the wire-cloth thickness by rolling changes the airflow markedly through the cloth, and in some instances combined brazing and rolling have a still greater effect on airflow. For example, at a given value of the pressure-drop parameter, a brazed sample that was reduced 42 percent in thickness passed only about one-fifth as much airflow as was passed by the unbrazed sample. However, the airflow through the sample that was reduced about 23 percent in thickness was nearly the same whether brazed or unbrazed. It was found that a brazed-rolled wire cloth in most cases was too brittle and stiff to readily form into shapes such as might be required for a turbine blade. The experimental turbine blade reported in reference 3 had a shell fabricated from a rolled unbrazed sheet of wire cloth.

In the design of blades and possibly other apparatus, variations in permeability in one or more directions may be required. For instance, reference 4 shows that both spanwise and chordwise variations in permeability are necessary for a turbine blade to maintain the cooling-air requirements at a minimum. The effect of chordwise variation in permeability can be partially accomplished by using a constant-permeability shell in conjuction with orifices at the blade base (ref. 4). As a consequence, only spanwise variations in permeability need to be achieved.

It would appear that taper-rolling of wire cloth would provide the necessary permeability variation and that references 1 and 2 could be used to determine the thickness to which the cloth should be rolled to obtain this permeability variation. Such a procedure presumes that the geometry or distortion of the wires of a cloth rolled with a taper is the same as when rolled flat, so that for comparable thickness both cloths would have the same permeability.

The purpose of the present report is to determine whether the data for taper-rolled wire cloth are in agreement with those of a flat-rolled cloth, what effect rolling a wire cloth with the taper parallel and perpendicular to the many wires has on permeability, and whether variations in permeability required for a turbine blade operating at gas and shell temperatures of 2500° and 1000° F, respectively, can be obtained within a sheet of material by taper-rolling. For the purpose of this report, the spanwise permeability variation of this turbine blade was selected as an example for duplication. A stainless-steel wire cloth with 20×200

mesh was used, since the permeability characteristic of this mesh cloth when rolled approaches the blade requirements. This investigation was conducted at the NACA Lewis laboratory.

SYMBOLS

A	total porous surface area
C_1	viscous-resistance coefficient
C_2	inertial-resistance coefficient
f_1, f_2	functions
G	mass rate of airflow, ρV or w/A
K	permeability coefficient
p	pressure
Δp^2	$p_i^2 - p_e^2$
R	gas constant
t	static temperature
V	flow velocity through porous wall (based on A)
w	weight flow
μ	absolute viscosity
ν	kinematic viscosity
ρ	density
τ	thickness of porous wall

Subscripts:

e	side of porous material at low pressure
i	side of porous material at high pressure
0	NACA standard temperature of 519° R

DEVELOPMENT OF SAMPLE

The AISI type 304 stainless-steel wire cloth used in this investigation, which is commercially available, has a mesh of 20×200, with wire diameters of 0.011 inch for the 20 wires and 0.010 inch for the 200 wires. The average thickness of the cloth as manufactured was 0.0307 inch. Figure 1 shows an enlarged photograph of a piece of the cloth. Ranges of tapering thickness considered herein for the wire-cloth samples are applicable to a shell of a transpiration-cooled turbine blade. The method for obtaining these ranges is given in detail in reference 4 and is briefly described as follows:

(1) Ratios of permeability to thickness K/τ over the blade span were calculated for the coolant passage around the blade, as illustrated in figure 2(a). Design conditions for the blade were for operation in a modified turbojet engine operating at a gas temperature of 2500° F and a shell temperature of 1000° F.

(2) An approximate equation that gives the pressure-drop parameter as a function of the airflow parameter and K/τ,

$$\Delta p^2 \frac{\mu_0^2 t_0}{\mu^2 t} = f_1\left(\frac{K}{\tau}, \frac{G\mu_0}{\mu}\right)$$

was used to determine $\Delta p^2 \mu_0^2 t_0/\mu^2 t$ values for varying values of $G\mu_0/\mu$. These calculations were made for K/τ values taken from the envelope of the curves in figure 2(a) for the root, mean, and tip sections.

(3) By superimposing these data (pressure drop against airflow parameter) on data taken from reference 2 for the flat-rolled 20×200-mesh wire cloth, the required shell thicknesses were approximated, as shown in figure 2(b).

(4) The thicknesses τ were plotted along the blade span as illustrated in figure 2(c). A curve was then drawn through the data to define the linear taper required in the wire-cloth sheet.

Four sheets approximately 4 by $5\frac{1}{2}$ inches were used as samples. A sheet of these dimensions is approximately that needed to form a turbine blade shell. Two sheets were rolled with a taper of 0.0044 inch per 3.93 inches of length, with the direction of taper in one sample parallel to the 200 wires and in the other sample perpendicular to the 200 wires. The thickness of the sheet over the 3.93-inch length tapered from a thickness of 0.0181 at one edge to 0.0225 inch at the other. This represents a reduction from the original cloth thickness of from 41.1 to 26.7 percent, respectively. Two more sheets were rolled in the same manner with end

thicknesses of 0.0151 to 0.0191 inch (thickness reductions of 50.8 and 37.8 percent, respectively) over the 3.93-inch length. The taper was also oriented parallel and perpendicular to the 200 wires. An enlarged photograph of a typical rolled sheet sample is shown in figure 3. The 0.0181- to 0.0225-inch tapered sheet was rolled to obtain the permeability variation from tip to root for the blade design considered herein. This is representative of the envelope of the curves in figure 2(a). The 0.0151- to 0.0191-inch tapered sample covers the lower permeability limit that would be encountered in this blade design. One of the lower curves in figure 2(a) could represent this limit.

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Tapering the wire cloth parallel to the 200 wires is considered because of the strength characteristics of the material. A shell fabricated from this sample can be oriented so that the high tensile-strength characteristics of the material are in the direction of the centrifugal force. Rolling a taper in the material oriented perpendicular to the 200 wires may form the many wires into uniform flat ribbons, since the centerline of the wire is perpendicular to the axis of the rolls. This may give a greater variation in permeability than the sample tapered parallel to the 200 wires (centerline of the 20 wires perpendicular to the roller axis) and was therefore considered. From current design practices, where the shell of a turbine blade is bonded to an inner supporting structure (see ref. 4), a blade fabricated with a shell tapered in this manner would have favorably high shear-strength characteristics.

Smaller samples were taken from each sheet as shown in figure 4. The samples consisted of disks $1\frac{1}{2}$ inches in diameter. The maximum and minimum thicknesses of each rolled sheet and disk were measured with micrometers, and the disk tapering thicknesses are given in table I with their identification symbols.

APPARATUS

Rolling Mill

A rolling mill was used to taper-roll the wire cloth. A schematic drawing of the mechanism of this mill is shown in figure 5. A 25-horsepower motor drives the upper and lower backup rolls, which are 8 inches wide and 8 inches in diameter. The backup rolls in turn drive the upper and lower work rolls which are 8 inches wide and $2\frac{1}{2}$ inches in diameter. The specimen to be rolled is fed between these work rolls. Pressure is exerted by a manual hydraulic pump that forces the lower backup and work rolls against the specimen, which in turn is forced against the upper work roll. The upper backup and work rolls are adjusted for the thickness with which the specimen is to be rolled.

In order to taper the wire cloth, shims are placed on one side of the mill between the bearing block and the height adjustment for the upper rolls. In this manner the upper rolls are tilted while the lower rolls remain horizontal. By this method the wire cloth was taper-rolled to the required thickness. It can be seen from table I that the dimensions were duplicated on the rolling mill within 0.0002 inch.

Airflow Apparatus

A schematic diagram of the equipment used to measure the airflow and the pressure drop through the wire-cloth samples is presented in figure 6. The method of sealing the sample disk is also shown in figure 6 and described in detail in references 1 and 2. Service air at a pressure of 120 pounds per square inch gage was drawn from the laboratory supply line and passed through the filter and pressure regulator. The airflow quantity was controlled by a hand valve and measured by a rotameter before flowing through the wire cloth. The air was discharged into the room. Air temperatures were measured with thermocouples upstream of the cloth sample. Static pressures were measured with water and mercury manometers upstream and downstream of the sample disks (airflow diam., 1.31 in.). This apparatus is explained in more detail in references 1 and 2.

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DATA CORRELATION METHOD

Correlation Equation

The data in this investigation were correlated by the basic method of reference 5. The mass velocity of a gas through a porous wall is a function of the difference in the squares of the pressure acting across the wall. The relation is given in reference 6 as

$$\frac{p_i^2 - p_e^2}{\tau} = C_1(2Rt\rho\nu)(\rho V) + C_2 2Rt(\rho V)^2 \qquad (1)$$

where C_1 and C_2 are constants that must be determined experimentally for each specimen (see ref. 1). When equation (1) is rearranged, the following expression can be written, as shown in reference 2:

$$\frac{G}{\mu} = f_1\left(\frac{p_i^2 - p_e^2}{\mu^2 t\tau}\right) \qquad (2)$$

By introducing μ and $\mu_0^2 t_0$ to reduce the data to NACA standard conditions (ref. 2), equation (2) can be written as

$$\frac{G\mu_0}{\mu} = f_2\left(\frac{p_i^2 - p_e^2}{\tau}, \frac{\mu_0^2 t_0}{\mu^2 t}\right) \tag{3}$$

The data for the porous samples in this investigation can then be plotted with the pressure-drop parameter $\log_{10}\left[\left(p_i^2 - p_e^2\right)\left(\frac{\mu_0^2 t_0}{\mu^2 t}\right)\right]$ against the airflow-rate parameter $G\mu_0/\mu$ for various values of wire thickness τ. The pressure-drop parameter is directly related to the permeability (ref. 2). This parameter is also readily obtainable and directly applicable to design procedures. For these reasons, the pressure-drop parameter may be used herein interchangeably with permeability.

Experimental Variables

From the permeability requirements of the blade design considered herein, it was determined that the airflow rate G must vary from about 0.0003 to 0.07 pound per second per square inch. To achieve this range in G, weight flow w was varied from about 0.00037 to 0.0904 pound per second. In general, to obtain these weight flows, the air supply pressure was varied from 0.50 inch of water to 100 inches of mercury. The weight flow w was measured on a rotameter. NACA standard temperature t_0 was taken as 519° R, and the value of μ_0 used was 121×10^{-7} pound per foot-second.

RESULTS AND DISCUSSION

Taper-Rolled Cloth

Taper parallel to the 200 wires. - The effects on the pressure-drop parameter over a range of airflow rates for the first sample of the 20×200-mesh wire cloth are shown in figure 7(a). This sheet (A) has the over-all tapered thickness of 0.0181 to 0.0225 inch, length of 3.93 inches, and the taper direction parallel to the 200 wires. The data indicate only a slight variation in the pressure-drop parameter for the three sampling disks. For values of $G\mu_0/\mu$ from about 0.0006 to 0.07, $\log_{10}\left[\Delta p^2 \mu_0^2 t_0/\mu^2 t\right]$ varied from about -0.3 to 3.5.

The data for three disks taken from the second wire-cloth sheet sample rolled with the taper parallel to the 200 wires and having an over-all thickness tapering from 0.0151 to 0.0190 inch are shown in figure 7(b). The data for the individual sampling disks fall on separate curves. The pressure-drop parameter increased with decreasing over-all thicknesses of the sample disks. It should be noted that, for constant values of

$G\mu_0/\mu$, an increase in the $\Delta p^2\mu_0^2 t_0/\mu^2 t$ term represents a decrease in permeability. The average percentage variations in the $\Delta p^2\mu_0^2 t_0/\mu^2 t$ parameter for the B1 and B2 sample disks with respect to the B3 sample disk are about 76 and 43, respectively. The average values of $\log_{10}\left(\Delta p^2\mu_0^2 t_0/\mu^2 t\right)$ are about 0 and 3.2 for $G\mu_0/\mu$ values of 0.0006 and 0.05, respectively.

Comparison of figures 7(a) and (b) also shows that the data for sheet B fall slightly above the data for sheet A. Sample disk A1 of figure 7(a) also is in good agreement with the sample disk B3 of figure 7(b). It is expected that the data should fall in this manner, since two of the sample disk thicknesses overlap and the over-all thicknesses of the two remaining disks in figure 7(b) are reduced.

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Taper perpendicular to the 200 wires. - Figure 8 presents the data for the two remaining sample sheets rolled with a taper perpendicular to the 200 wires. The data for sheet C, with an over-all tapering thickness of 0.0181 to 0.0225 inch (similar to the taper of sheet A in fig. 7(a)), are shown in figure 8(a). An appreciable variation in the pressure-drop parameter for a given airflow parameter can be observed for the three sample disks. The average percentage variations in the $\Delta p^2\mu_0^2 t_0/\mu^2 t$ parameter for disks C1 and C2 with respect to disk C3 are about 400 and 140, respectively.

For sheet D rolled perpendicular to the 200 wires to an over-all tapering thickness of 0.0151 to 0.0191 inch, the range of airflow was limited because of the limiting operating pressure of the test facilities. The data, presented in figure 8(b), show that the spread in the pressure-drop parameter for disks D2 and D3 is comparable to that in figure 8(a), but displaced in the expected upward direction. The data for disk D1 indicate that rolling the wire cloth to a thickness below about 0.0166 inch results in very little effect on the pressure-drop parameter. This is approximately a reduction in original thickness of 50 percent. The expected overlapping of the data for disk C1 of figure 8(a) and disk D3 of figure 8(b) is apparent, as well as the fact that the remaining data of figure 8(b) fall above the data of figure 8(a).

Comparison of figures 7 and 8 clearly indicates that rolling a cloth with the taper perpendicular to the 200 wires gives a greater variation in permeability than rolling with a taper parallel to the 200 wires.

Only cloth samples with tapers obtained by rolling parallel and perpendicular to the 200 wires were investigated. It may be possible to obtain different degrees of variation in permeability by other methods of rolling; for example, feeding the wire through the rolling mill at some intermediate angle. A greater degree of permeability variation for the

case where the taper is parallel to the many wires may possibly be obtained. This might be accomplished by a rolling mill designed so that the many wires are introduced perpendicular to the roller axis. The taper may then be formed into the cloth by a cam arrangement that gradually closes or opens the gap between the rolls. The cam arrangement or forming rolls to a certain contour could be used to roll wire-cloth sheets if permeabilities other than those resulting from a linear taper are required.

Comparison of Taper- and Flat-Rolled Samples

The sample disks rolled with a taper perpendicular to the 200 wires were compared with data taken from figure 6(a) of reference 2. The cloth in reference 2 was also rolled with the roller axis perpendicular to the axis of the 200 wires. This comparison is shown in figure 9, where the pressure-drop parameter is plotted against the airflow parameter. (Similar values of thickness for data of ref. 2 were obtained from cross-plots.) In the following comparisons, the average of the maximum and minimum thicknesses is used as the thickness of the tapered disks. Data of disk D1 are not shown, since these data are out of the range of the data in reference 2. Sheets A and B are not compared, since they were rolled differently.

In this comparison the maximum and minimum average differences for the pressure-drop parameter between the tapered and flat-rolled samples ranged from 216 to 68 percent. The discrepancy in the data could be caused by the difference in wire geometry assumed for the two methods of rolling or by the difficulties encountered by the manufacturer in duplicating identical wire cloths, since a period of about 4 years elapsed between the two investigations.

Inasmuch as the data obtained herein consistently fall above those of reference 2, the data for flat-rolled wire may be useful for taper-rolling application if a correction factor is determined. This can be accomplished by plotting the data obtained herein with that given in reference 2 in terms of thickness for similar pressure-drop and airflow conditions. This plot is presented in figure 10. It is apparent from the figure that a correction in thickness averaging about 8 percent would bring the data into good agreement.

In figure 11 the dashed curves represent the spread in the pressure-drop parameter required from root to tip of a turbine blade for the calculation considered herein using the data of reference 2. The average difference in the pressure-drop parameter is about 325 percent. The solid lines represent the spread obtained from a sample sheet (sheet C) in attempting to duplicate the calculated permeability requirements. The average difference in the pressure-drop parameter is about 400 percent, slightly more than the required spread. The displacement of the curves has been discussed previously.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effects of taper-rolling a wire cloth on permeability:

1. Rolling a 20×200-mesh wire cloth with a taper parallel to the 200 wires has only a slight effect on permeability or pressure-drop parameter; however, rolling the cloth with the taper perpendicular to the 200 wires has an appreciable effect on permeability.

2. The data of the taper-rolled samples fall from 68 to 216 percent above the data for flat-rolled samples of comparable thicknesses reported previously. For equal pressures and airflows across these samples, however, the differences in thickness of the flat- and taper-rolled samples amounts to approximately 8 percent.

3. The required range of spanwise permeability variation, determined by currently known design procedures for a blade operating with a shell temperature of 1000° F and a gas temperature of 2500° F, can be reached by rolling a 20×200-mesh wire cloth with a taper perpendicular to the 200 wires.

4. Reducing the original wire thickness more than 50 percent results in little change in the pressure-drop parameter.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 10, 1956

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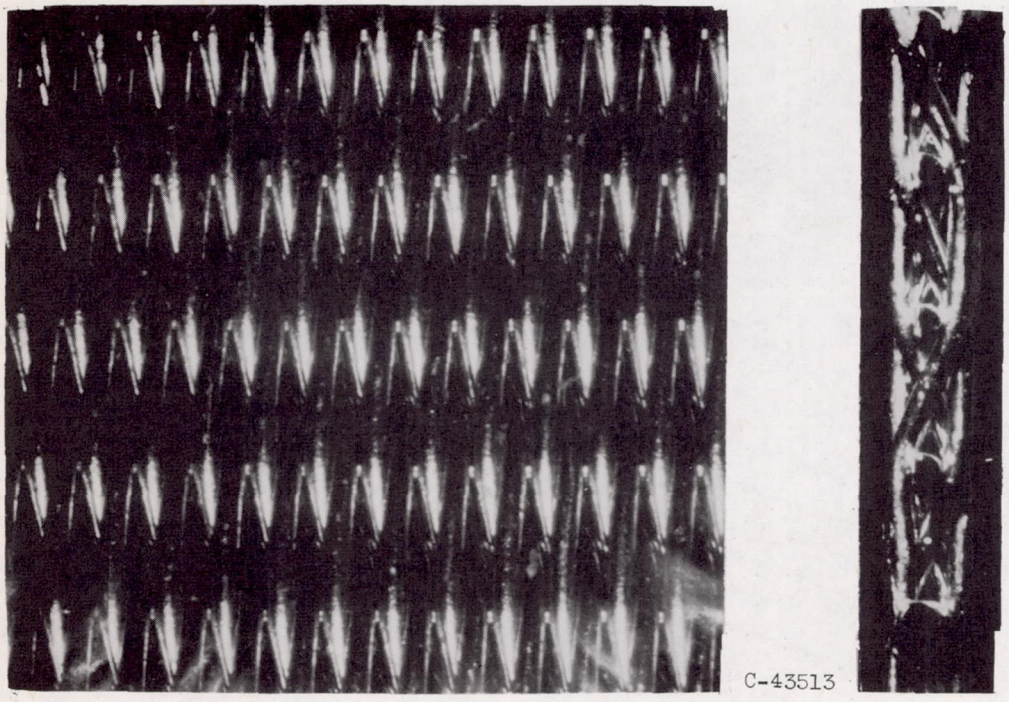
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6. Eckert, E. R. G., Livingood, John N. B., and Prasse, Ernst I.: One-Dimensional Calculations of Flow in a Rotating Passage with Ejection Through a Porous Wall. NACA TN 3408, 1955.

TABLE I. - MAXIMUM, MINIMUM, AND AVERAGE THICKNESSES OF TAPER-ROLLED DISKS MEASURED ON 1.31-INCH DIAMETER

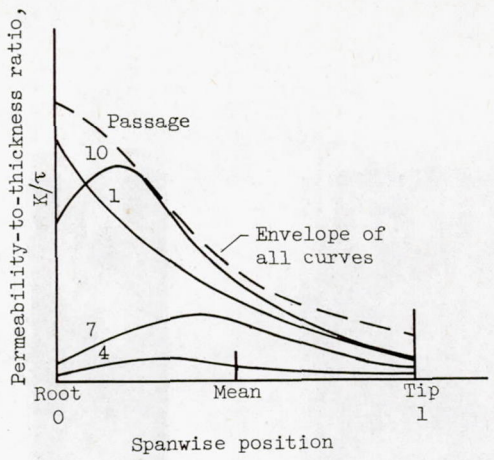
Sheet	Disk	Min. thickness, in.	Max. thickness, in.	Av. thickness, in.
Taper parallel to 200 wires				
A	1	0.0181	0.0196	0.0188
	2	.0196	.0212	.0204
	3	.0212	.0225	.0218
B	1	0.0151	0.0164	0.0158
	2	.0164	.0177	.0170
	3	.0177	.0190	.0184
Taper perpendicular to 200 wires				
C	1	0.0181	0.0196	0.0188
	2	.0196	.0211	.0204
	3	.0211	.0225	.0218
D	1	0.0151	0.0165	0.0158
	2	.0166	.0179	.0172
	3	.0179	.0191	.0185

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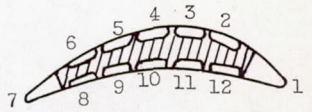


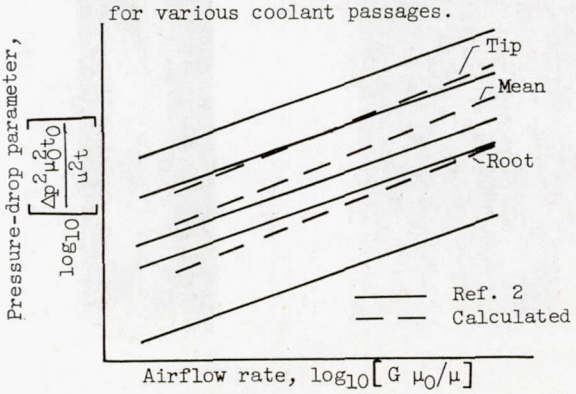
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Figure 1. - Wire cloth as manufactured (×15).

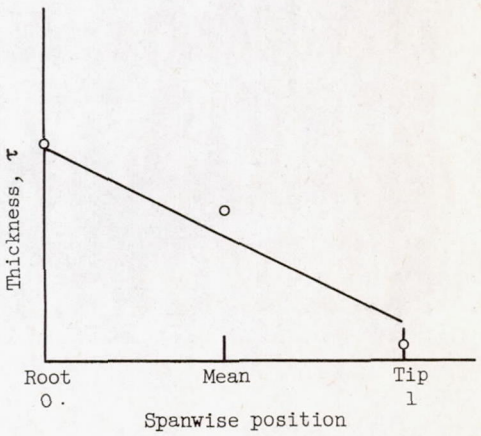


(a) Variation of permeability-to-thickness ratio with blade span for various coolant passages.





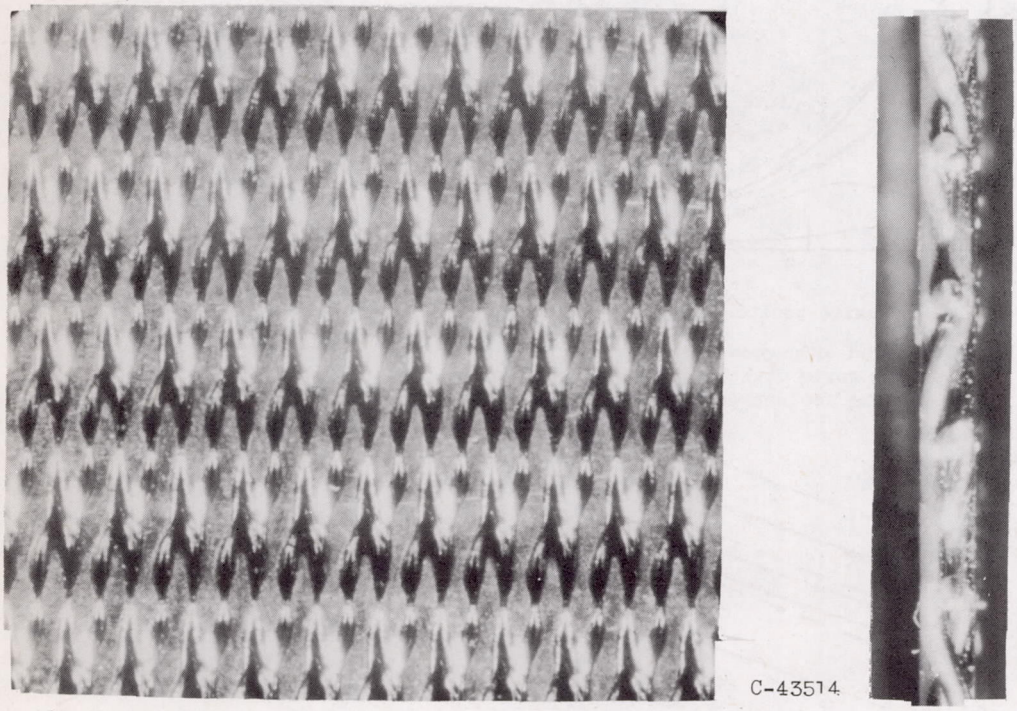
(b) Variation of pressure-drop parameter with airflow parameter for tip, mean, and root section of blade.



(c) Linear thickness variation with span.

Figure 2. - Illustrative graphs for determining spanwise thickness variation for turbine blade.

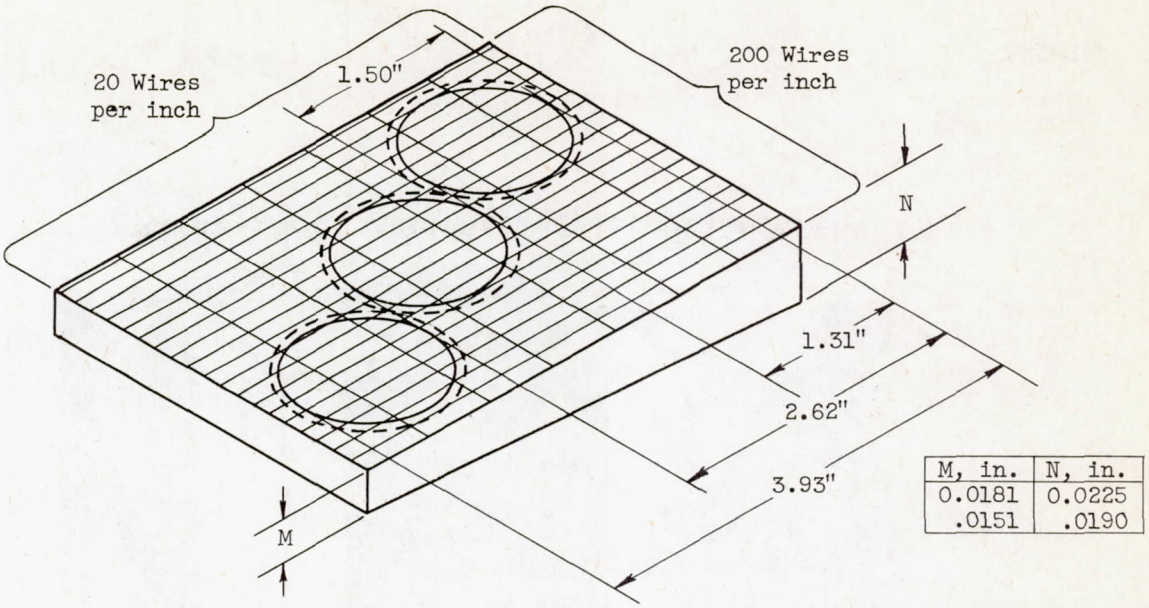
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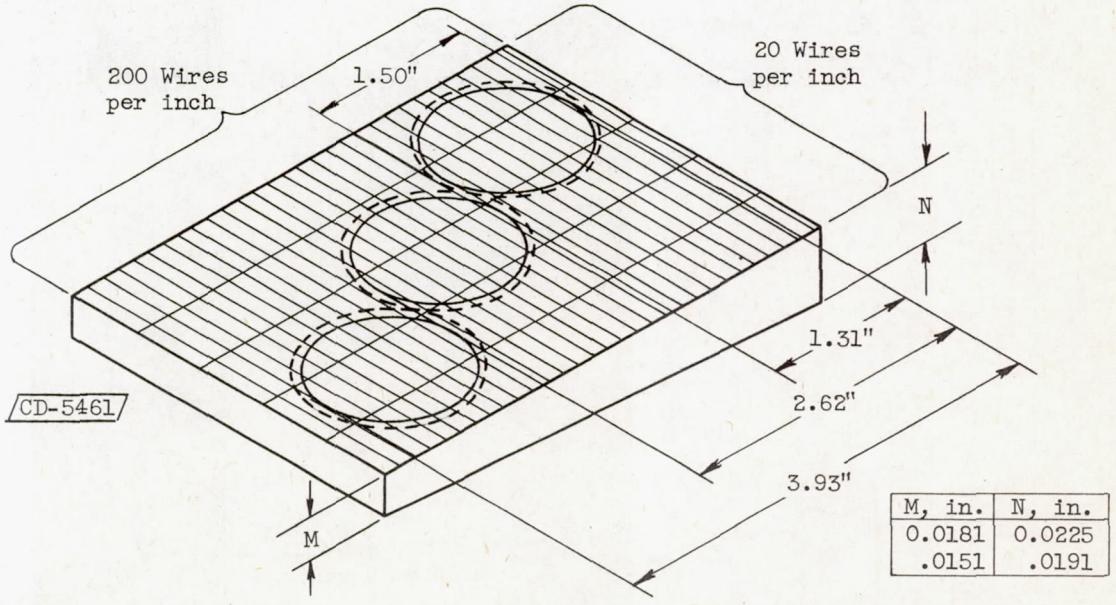
Figure 3. - Taper-rolled sample of wire cloth (×15).

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M, in.	N, in.
0.0181	0.0225
.0151	.0190

(a) Taper parallel to 200 wires.



M, in.	N, in.
0.0181	0.0225
.0151	.0191

(b) Taper perpendicular to 200 wires.

Figure 4. - Schematic drawing showing disks as cut from wire cloth.

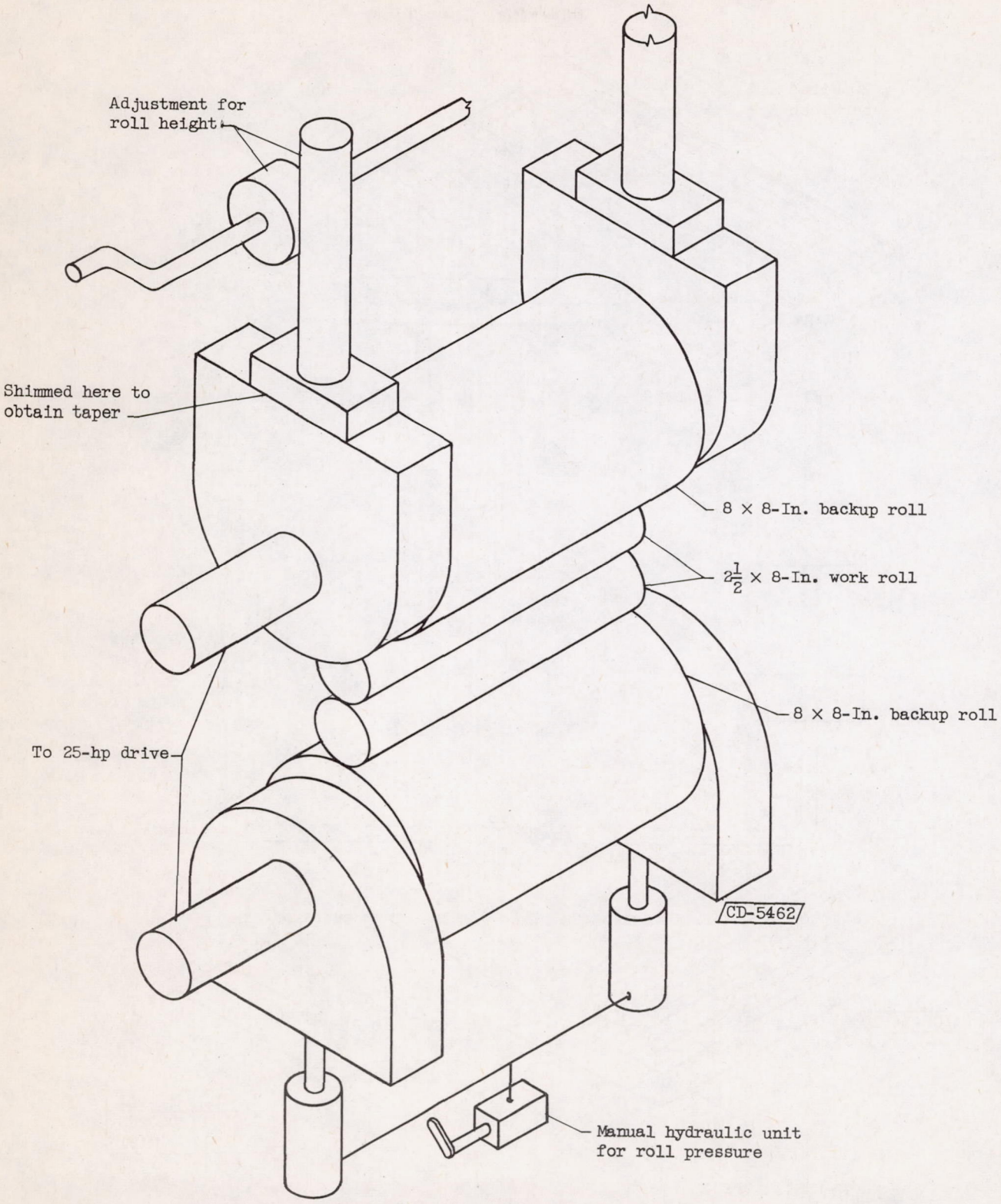


Figure 5. - Schematic drawing of rolling mill.

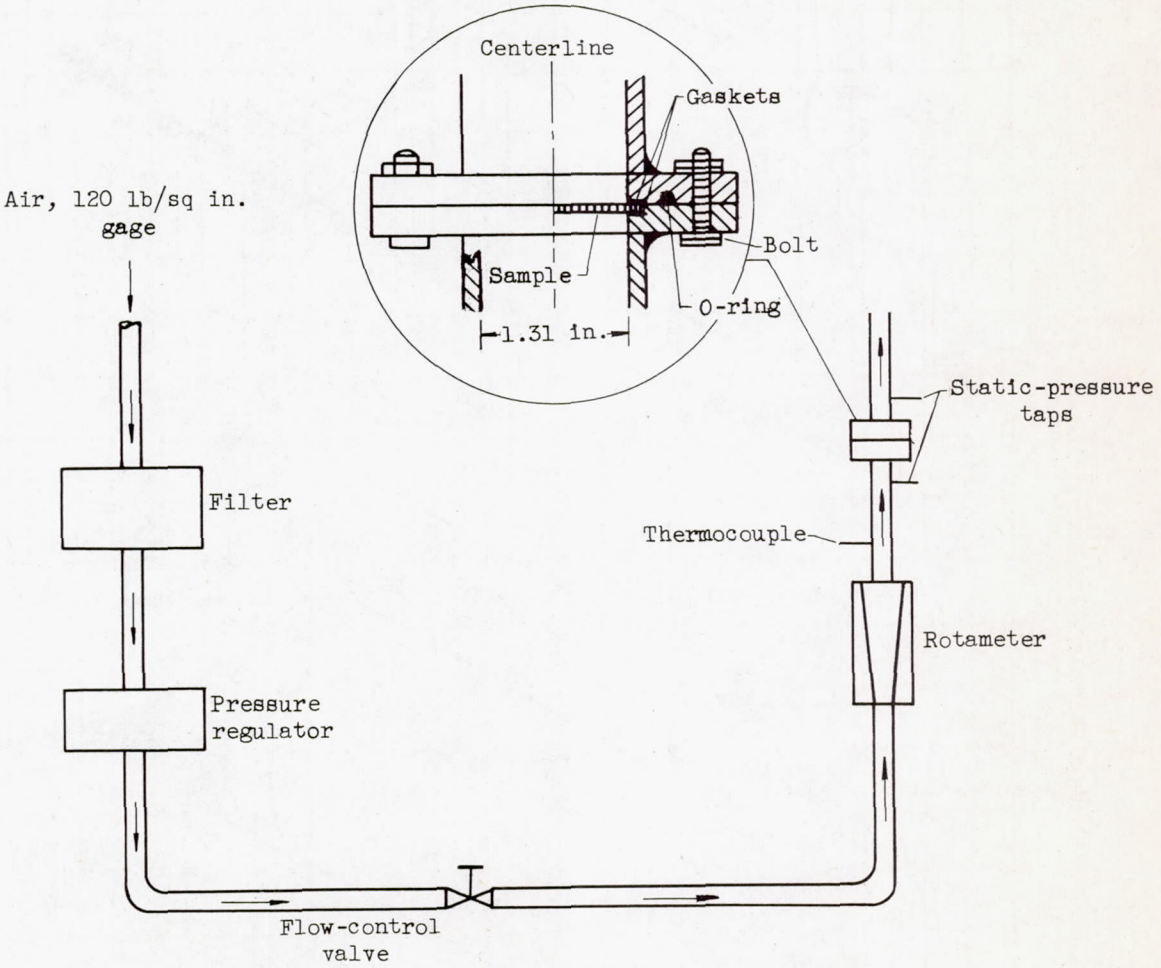
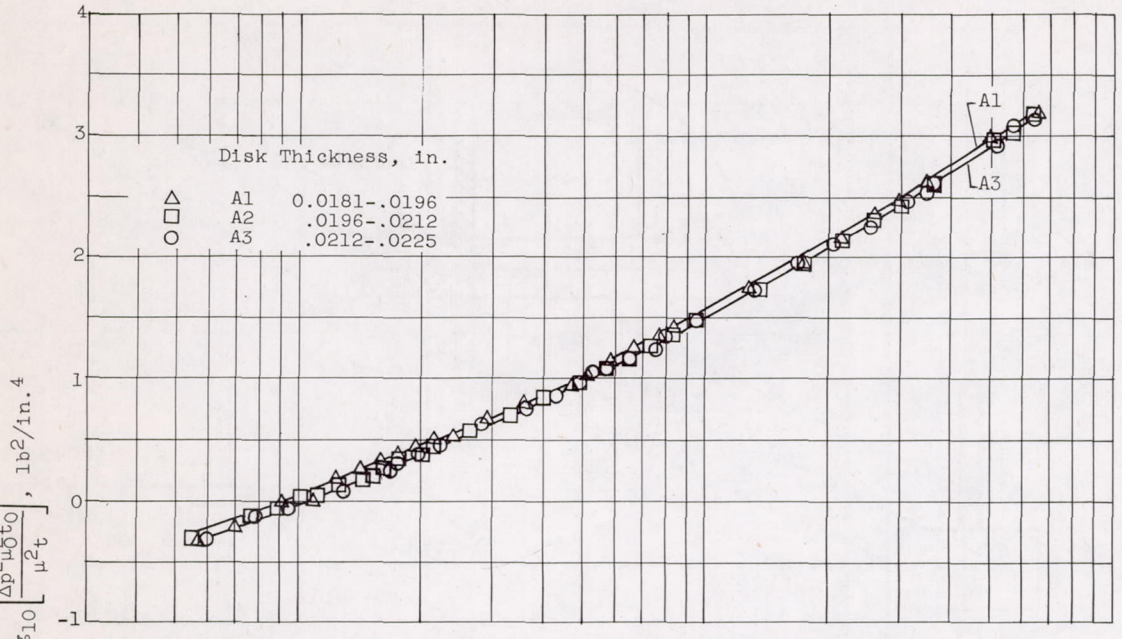
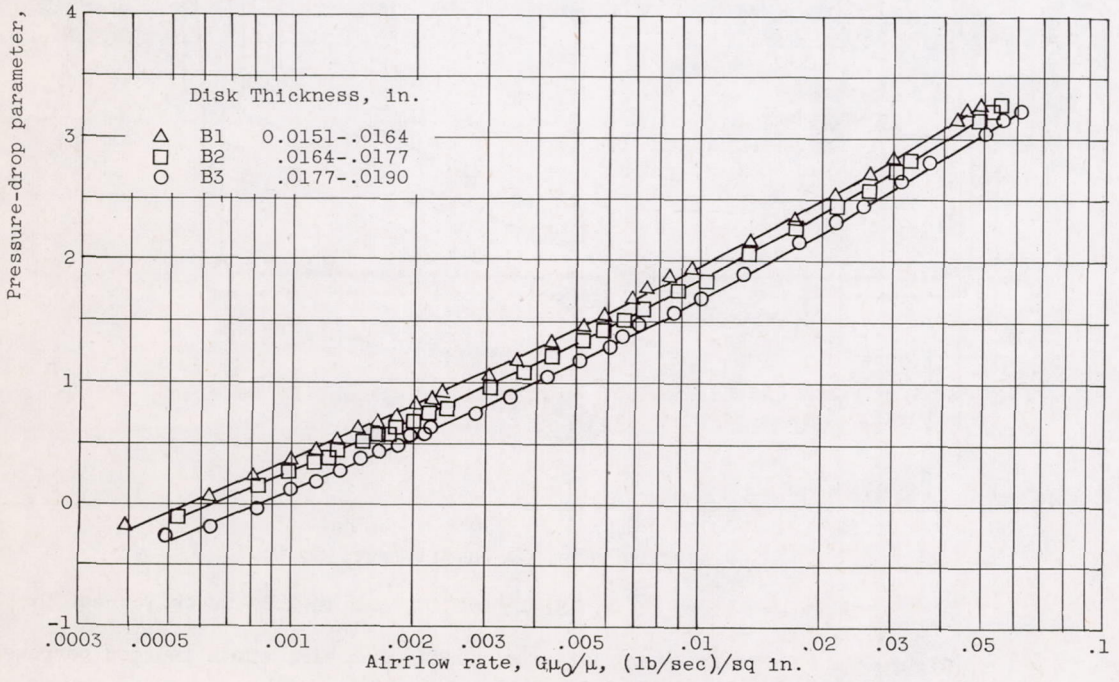


Figure 6. - Schematic diagram of equipment for measuring air-flow through disks of wire cloth.

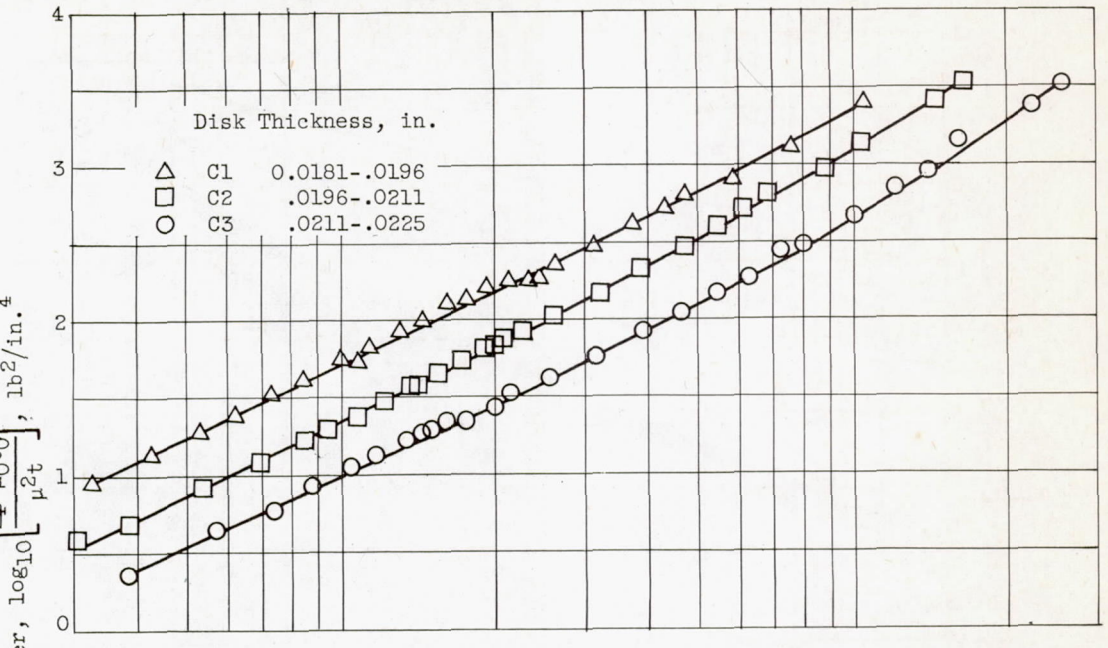


(a) Thickness taper of 0.0181 to 0.0225 inch in 3.93 inches; sheet A.

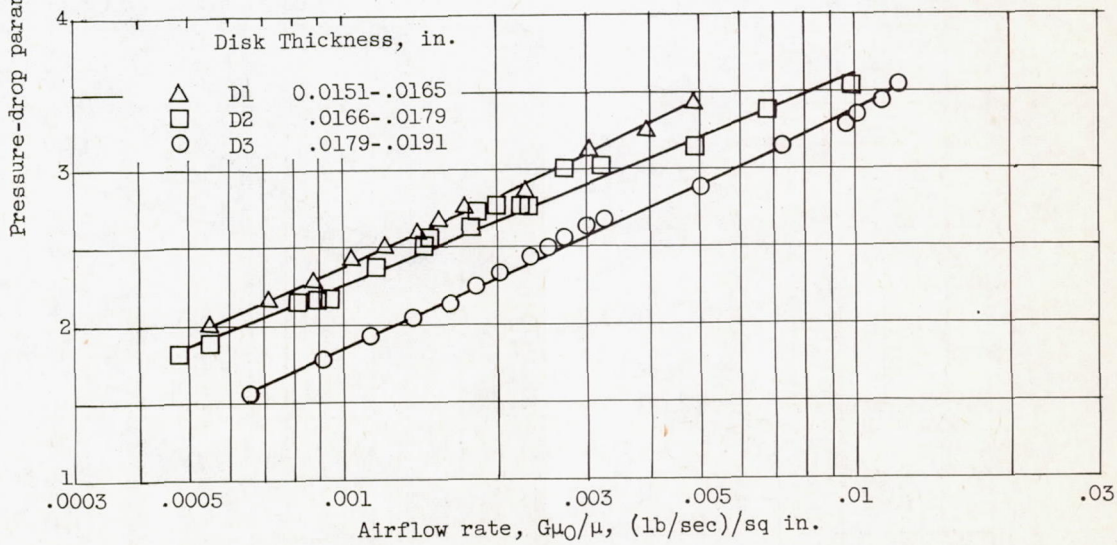


(b) Thickness taper of 0.0151 to 0.0190 inch in 3.93 inches; sheet B.

Figure 7. - Correlation of data for 20x200-mesh wire cloth tapered parallel to the 200 wires.



(a) Thickness taper of 0.0181 to 0.0225 inch in 3.93 inches; sheet C.



(b) Thickness taper of 0.0151 to 0.0191 inch in 3.93 inches; sheet D.

Figure 8. - Correlation of data for 20X200-mesh wire cloth tapered perpendicular to the 200 wires.

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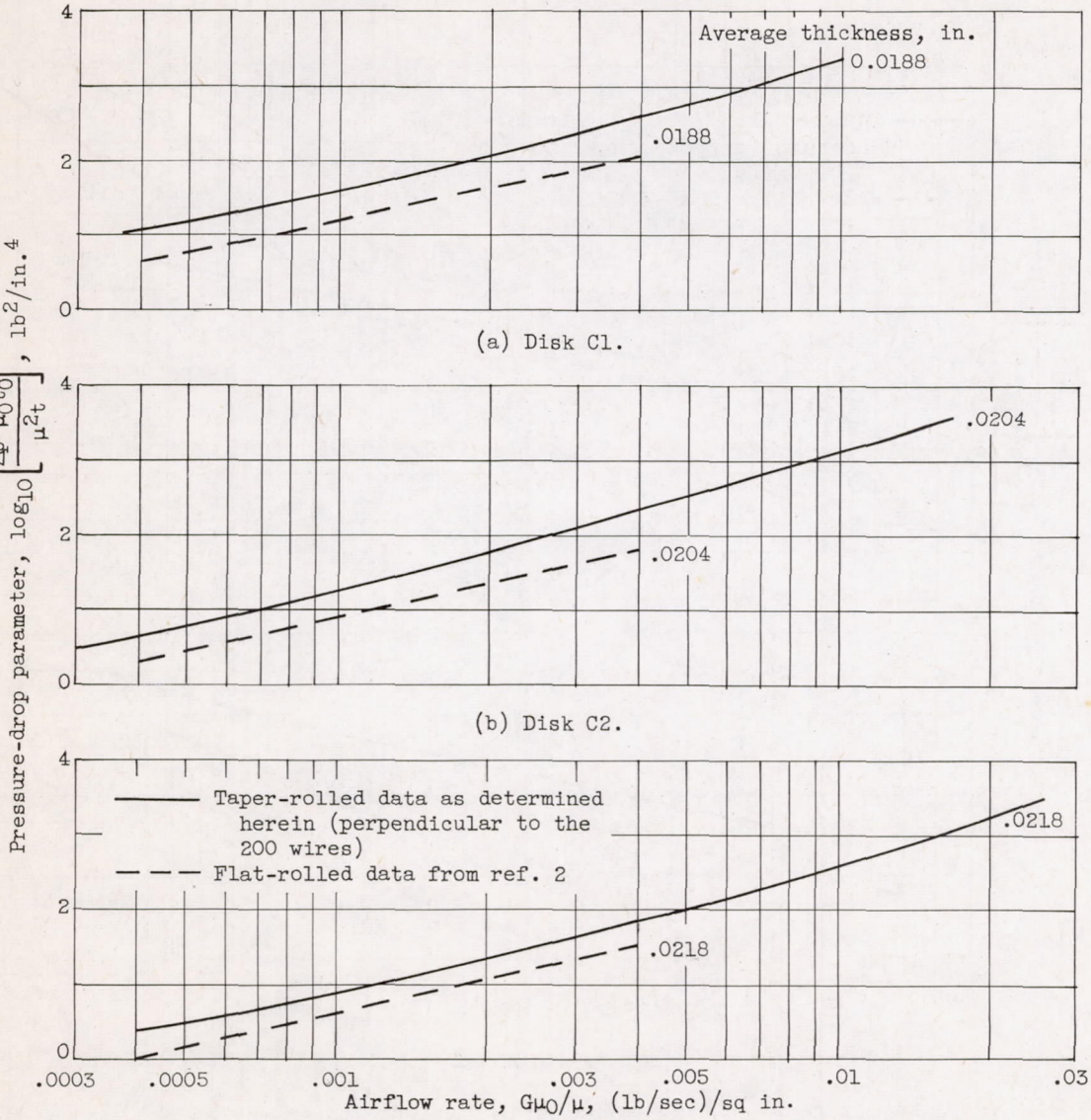
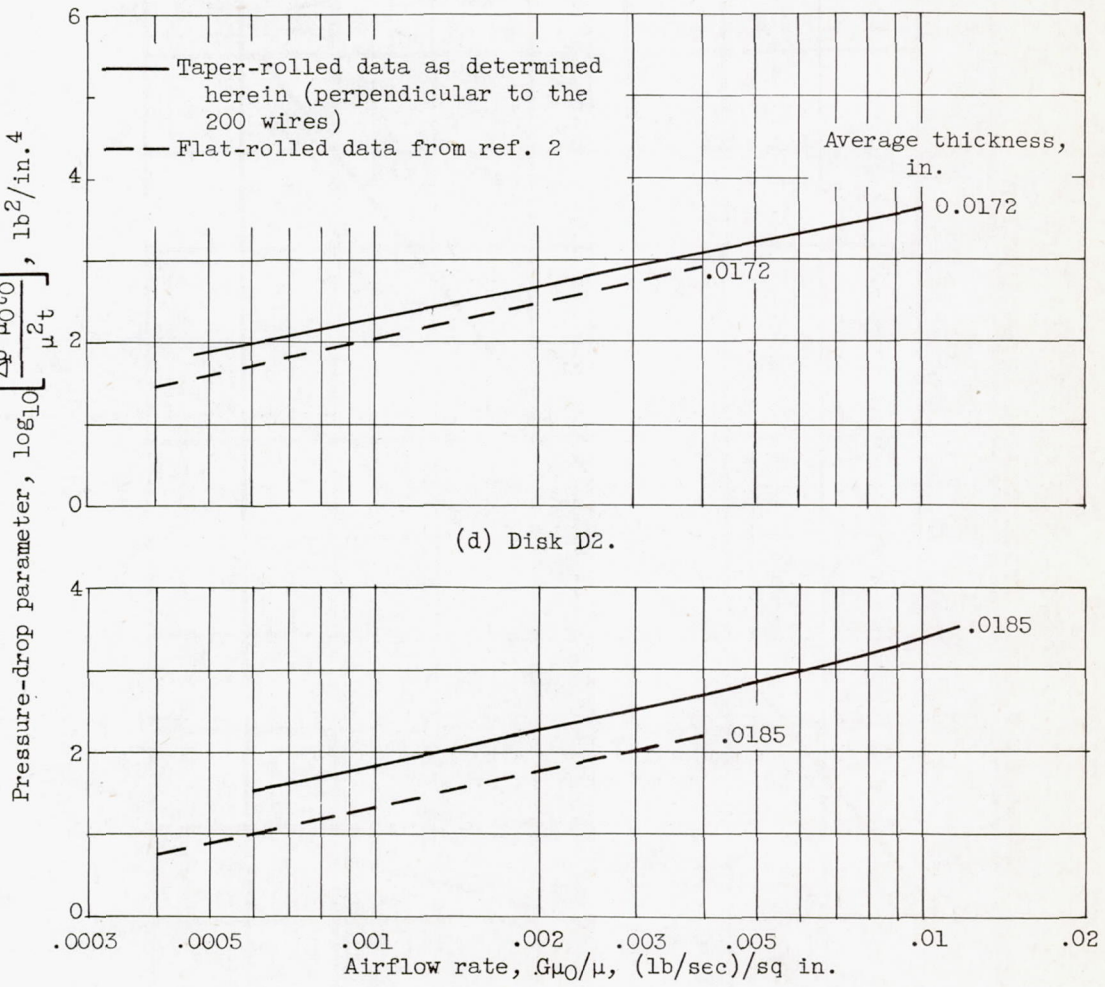


Figure 9. - Comparison of data for taper-rolled and flat-rolled wire cloth.

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(d) Disk D2.

(e) Disk D3.

Figure 9. - Concluded. Comparison of data for taper-rolled and flat-rolled wire cloth.

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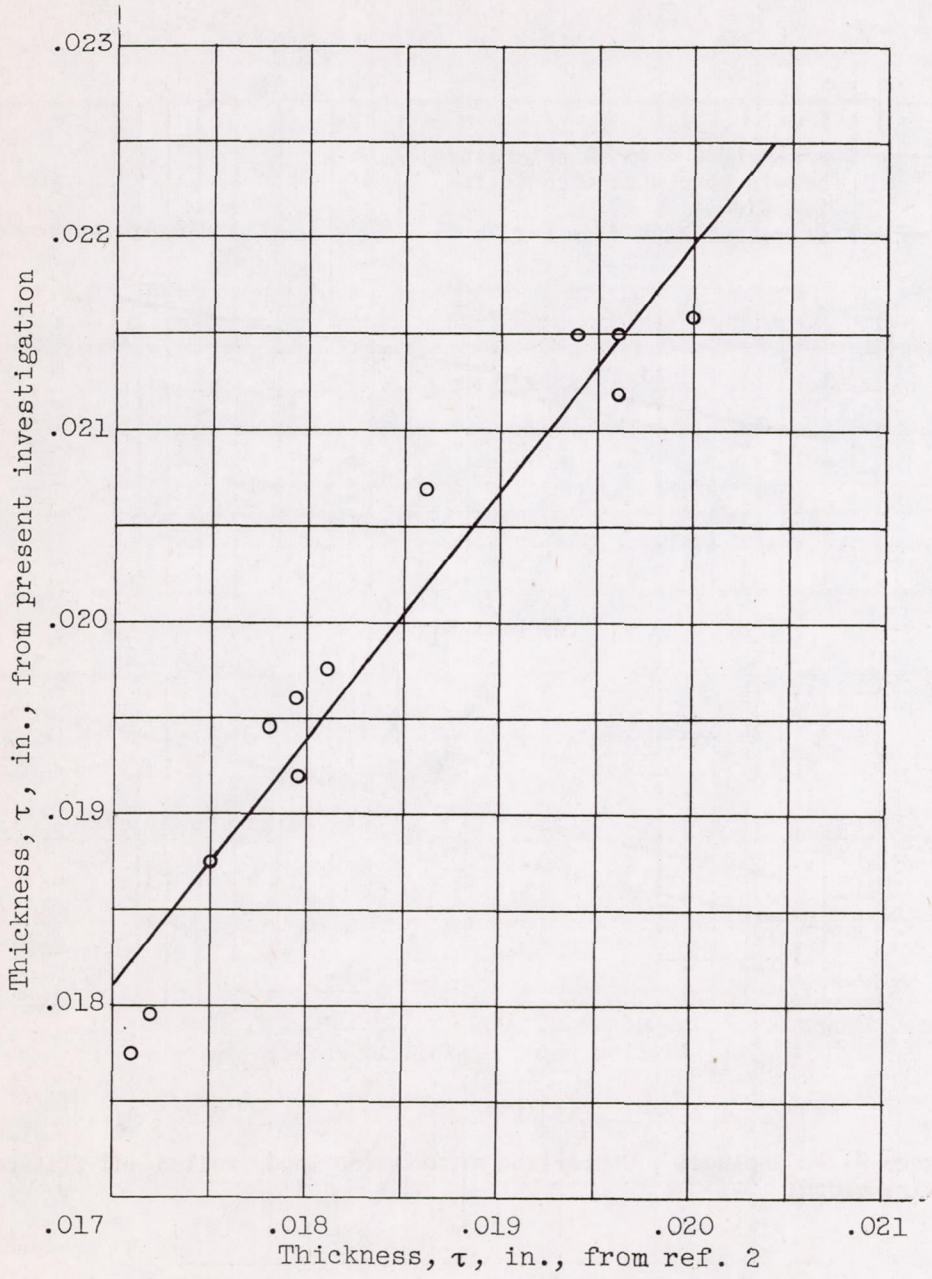


Figure 10. - Comparison of taper-rolled and flat-rolled 20X200-mesh wire-cloth thicknesses for similar pressure-drop and airflow parameters.

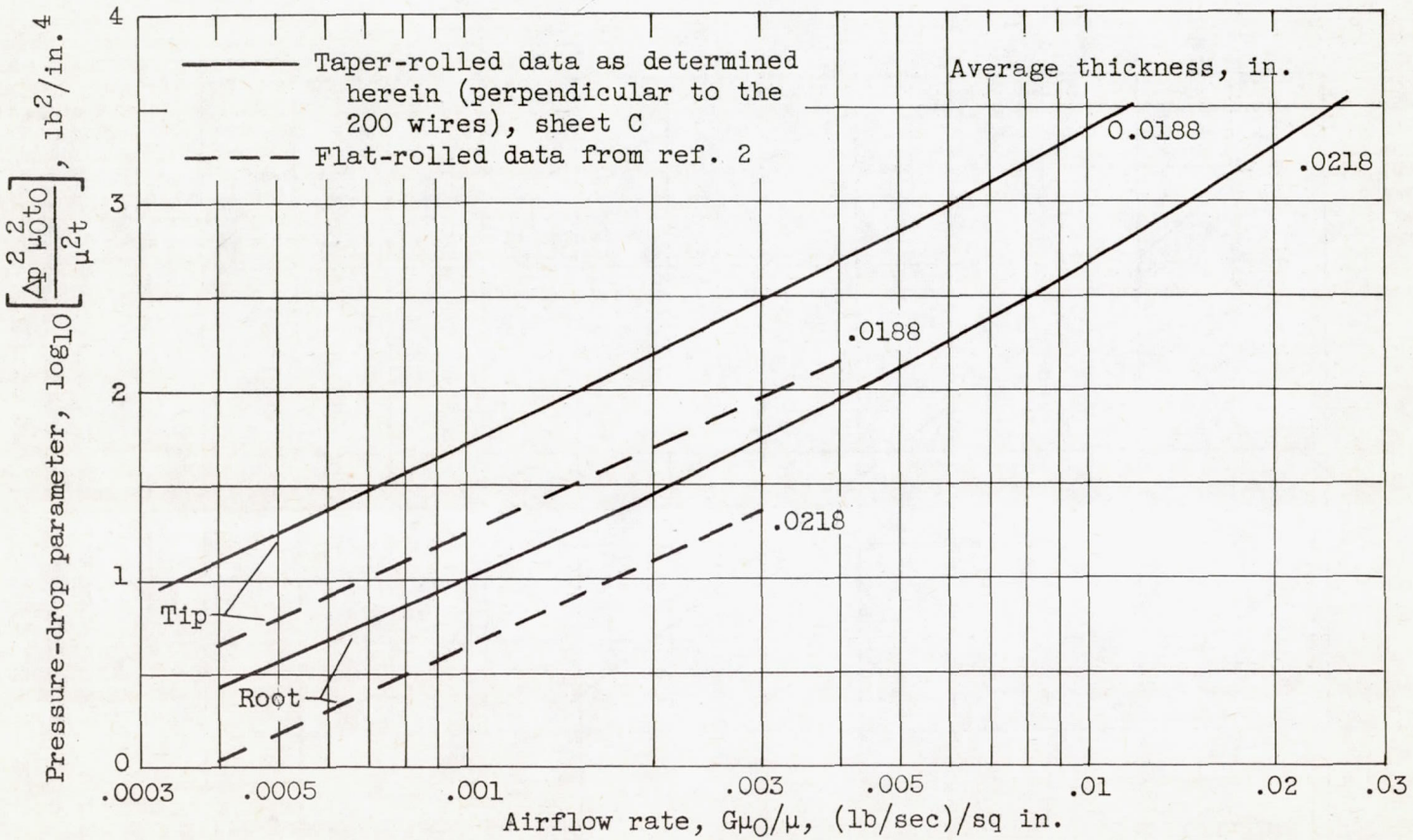


Figure 11. - Comparison of spread in permeability for turbine blade as determined from data of reference 2 and as obtained by taper-rolling.

NACA - Langley Field, Va.